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AN ASSESSMENT OF EXPLOITABLE BIOMASS AND PROJECTION OF MAXIMUM SUSTAINABLE YIELD FOR *HETEROCARPUS LAEVIGATUS* IN THE HAWAIIAN ISLANDS

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INTRODUCTION

The caridean shrimp, Heterocarpus laevigatus Bate 1888, is a common deepwater inhabitant of the Hawaiian Islands, where it is prized for its excellent flavor. Despite this, little interest existed in commercially harvesting this species, even after very encouraging catch statistics became available from two early resource surveys (Clarke 1972a, 1972b; Struhsaker and Aasted 1974), in which substantial quantities of H. laevigatus, and its shallower dwelling and smaller congener H. ensifer, were readily captured in baited traps. These pandalid shrimps were found in waters 200-375 fathoms[1] (365-685 m) deep, and based on catch rates that averaged 6.6 kg/trap around Oahu, the resource seemed sufficiently abundant to support a commercial fishery.

To date, however, commercial fishing efforts have met with limited success, although about 75 metric tons (t) of H. laevigatus were caught by one vessel during the 1983-84 fishing season (Tagami and Barrows 1988). At that time, a short-lived fishery involving as many as seven large (23- to 40-m) vessels had developed in Hawaii. Indications are that this large-scale operation failed to sustain itself because of problems with gear development, product processing, marketing, stock depletion, and overall corporate management. Nonetheless, due to the enthusiastic response of the public to the product, optimism regarding the economic viability of developing a stable shrimp fishery in Hawaii remains high.

With this ongoing, albeit sporadic, interest and activity in the shrimp fishery, increasingly apparent are the major gaps in our knowledge on the biology, ecology, and population dynamics of Heterocarpus shrimp stocks, especially in the Hawaiian Archipelago (Gooding 1984; Dailey and Ralston 1986). Particularly lacking are data concerning the absolute abundance of the H. laevigatus stock and its ability to withstand sustained fishing pressure, although research results from the Northern Mariana Islands (Ralston 1986; Moffitt and Polovina 1987) are available for comparative purposes. Subsequent to the burst of activity in 1983-84, the Western Pacific Regional Fishery Management Council (Council) reviewed the situation and recommended that a framework fishery management plan for deep-sea shrimp be prepared (Council 1984). A stock assessment of H. laevigatus was initiated in response to these developments.

The primary objective of the assessment was to determine the standing stock (i.e., exploitable biomass) of H. laevigatus in the Hawaiian Islands, including all islands and banks within the 200-mile Fishery Conservation Zone that extends from the Island of Hawaii to the Hancock Seamounts. Were such information available, the maximum sustainable yield (MSY) of the Hawaiian fishery could be estimated, by using the results presented in Moffitt and Polovina (1987), where the ratio of MSY to unfished standing stock was calculated under two different optimization criteria.

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[1]Depths are given in fathoms (1 fathom = 1.83 m) because nautical charts using this unit were extensively utilized in this study. On occasion, the equivalent in meters follows in parentheses.

To determine the exploitable biomass of shrimp at geographically discrete locations in Hawaii, the well-known formula

$$CPUE = q\ (B/A)$$

was used (Ricker 1975); where CPUE is the catch per unit of fishing effort, q is the catchability coefficient of the fishing gear, B is the exploitable biomass, and A is the area occupied by the stock. This relationship is based on the assumption that catch rate is strictly proportional to the density of stock (B/A) and that q is the proportionality constant relating these two quantities. By simple rearrangement, we have

$$B = \frac{(CPUE)(A)}{q} . \qquad (1)$$

Thus, to estimate the exploitable shrimp biomass at any particular island or bank we need to (1) obtain a randomized estimate of catch rate, (2) measure the habitat area over which the shrimp occur, and (3) calibrate the sampling gear (i.e., estimate q).

To accomplish these goals, the study was divided into four phases. First, potential sites of shrimp occurrence were identified and habitat areas measured by examining the bathymetry of the Hawaiian Islands. Second, a depletion experiment was conducted to estimate the catchability coefficient of the fishing gear. Third, a refined depth stratified sampling program for H. laevigatus was conducted around the Islands of Kauai and Niihau to establish the relationship between shrimp abundance and depth of capture and to determine an efficient allocation plan for future sampling efforts. Fourth, regional variation in shrimp abundance was studied by obtaining estimates of shrimp CPUE from widespread localities in the Hawaiian Archipelago.

METHODS

The Hawaiian Archipelago extends 1,600 nmi along a southeast-northwest axis, from the Island of Hawaii to Northwest Hancock Seamount (Fig. 1). Within this expanse, 7 discrete sites in the main Hawaiian Islands (MHI) and 31 sites in the Northwestern Hawaiian Islands (NWHI) were identified, based on depth criteria, as locations capable of sustaining H. laevigatus populations. Generally, each location was fully enclosed by an uninterrupted 500-fathom (915-m) isobath, the lower depth limit at which H. laevigatus is found in Hawaii (Gooding 1984; Dailey and Ralston 1986). Exceptions to this rule were made for Kauai and Niihau, which share the same 500-fathom contour; similarly, Oahu was distinguished from the much larger area encompassing Maui, Lanai, Kahoolawe, and Molokai. Moreover, the upper depth limit at which the species is found is about 250 fathoms (468 m). Therefore, the area bounded by the 250- and 500-fathom contours represents the extent of potential habitat of H. laevigatus and was the depth range studied.

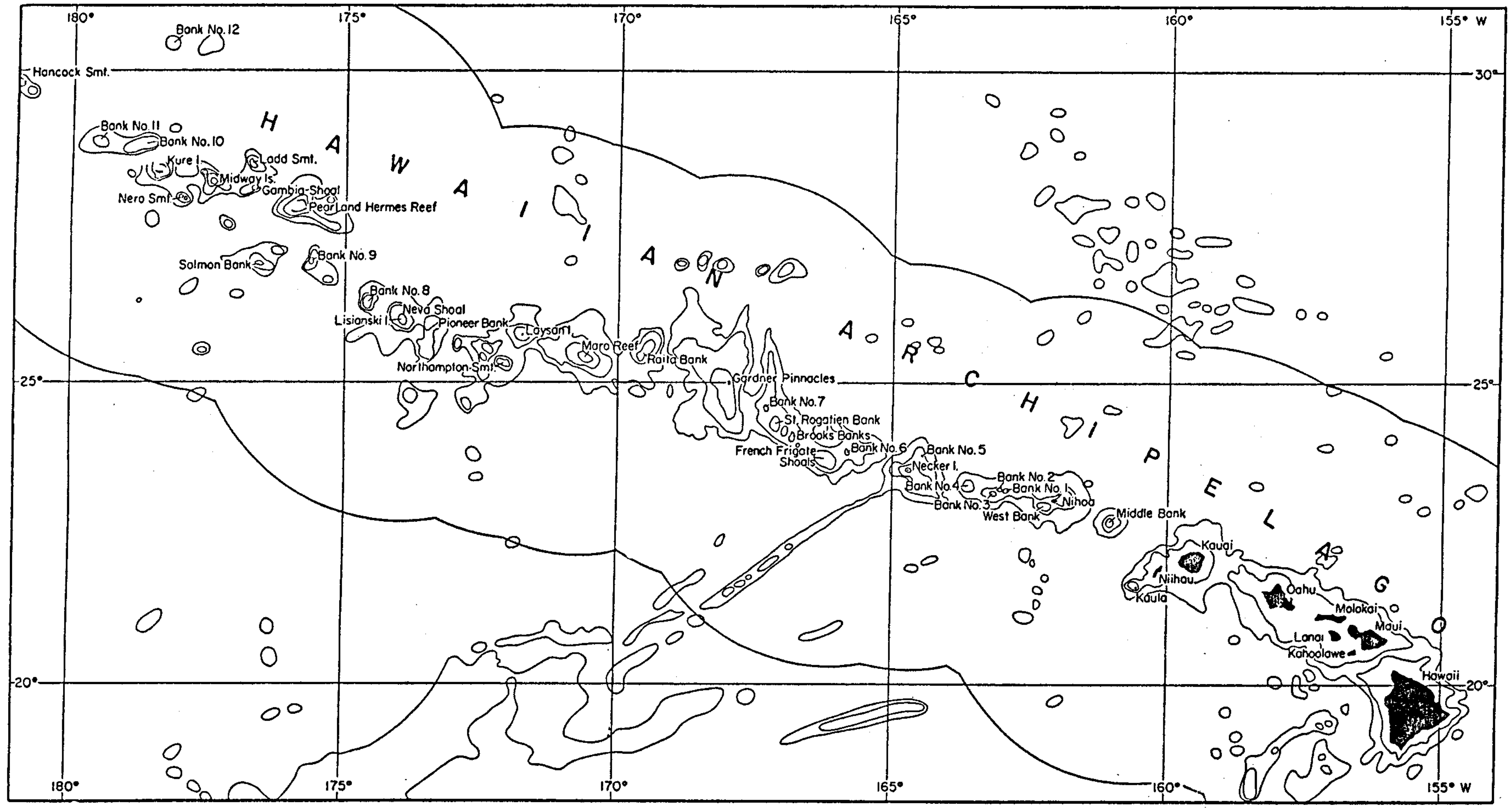

Figure 1.--The Hawaiian Archipelago, including the Northwestern Hawaiian Islands. The approximate positions of the 100-, 1,000- and 2,000-fathom isobaths and the U.S. Fishery Conservation Zone are shown on the map.

An estimate of the amount of suitable shrimp habitat (in square nautical miles; 1 nmi^2 = 3.43 km^2) at each of the 38 sites was obtained by determining the horizontal planar area lying between the 250- and 500-fathom isobaths, based on standard National Oceanic and Atmospheric Administration (NOAA) nautical charts (19016, 19019, and 19022) and Defense Mapping Agency bottom contour charts. Most maps specified the 500-fathom isobaths, but it was necessary to contour all of the 250-fathom isobaths by eye with the sounding data provided on the charts. A digitizing tablet equipped with a mouse was used to calculate all area estimates directly from the charts. Each contour was digitized three times by both authors, providing an indication of measurement error in our estimates of shrimp habitat area.

Since 1985, the Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service, NOAA, has conducted four research cruises aboard the NOAA ship _Townsend Cromwell_ to survey sites for this study. Standard fishing gear was utilized for all sampling of CPUE statistics. The gear employed was a top loading pyramid shrimp trap, identical in construction to those used by a commercial shrimp operation in 1983-84. Each trap was made of welded steel reinforcement bars, having a 1.87 x 1.87 m base, and an overall volume of 1.84 m^3, and was covered by 1.27 x 2.54 cm mesh hardware cloth. A full description of the gear is given in Tagami and Barrows (1988).

Typically, eight solitary traps were deployed daily and allowed to soak overnight. Traps were generally set in the afternoon and hauled the following morning, being in the water for a period of 16-20 h. All traps were baited with approximately 3 kg (6-7 lb) of chopped mackerel, _Scomber japonicus_. Upon retrieval of the gear, each trap was emptied, and the contents sorted by species, counted, and weighed to the nearest 0.01 kg. Routinely, random samples of roughly 200 _H. laevigatus_ were taken from the trap catches; carapace length, sex, and ovigerous condition were then recorded for length-frequency analysis.

Depletion Experiment

To estimate q, an intensive fishing experiment was conducted (see also Ralston 1986). Depletion experiments, including the Leslie method used here (Ricker 1975), have two restrictive assumptions. First, the population fished is closed, or equivalently, additions exactly balance removals other than those due to fishing. Second, fishing removals account for all changes in stock biomass, such that natural mortality, growth, and recruitment have negligible effects during the period of fishing. Thus, the best site for a depletion experiment is a naturally isolated, small area so that removals can be carried out over as short a time interval as possible.

A small rise midway in the Kaulakahi Channel (lat. 21°54.5'N, long. 159°56.5'W) separating Kauai and Niihau was chosen for the intensive fishing experiment. This nearly circular rise (Fig. 2), with a crest at 230 fathoms, has an area of 3.46 nmi^2 (horizontal planar area shallower than 350 fathoms) and is isolated from Kauai and Niihau by depths greater than 400 fathoms. The site lies in the required depth range for _H. laevigatus_,

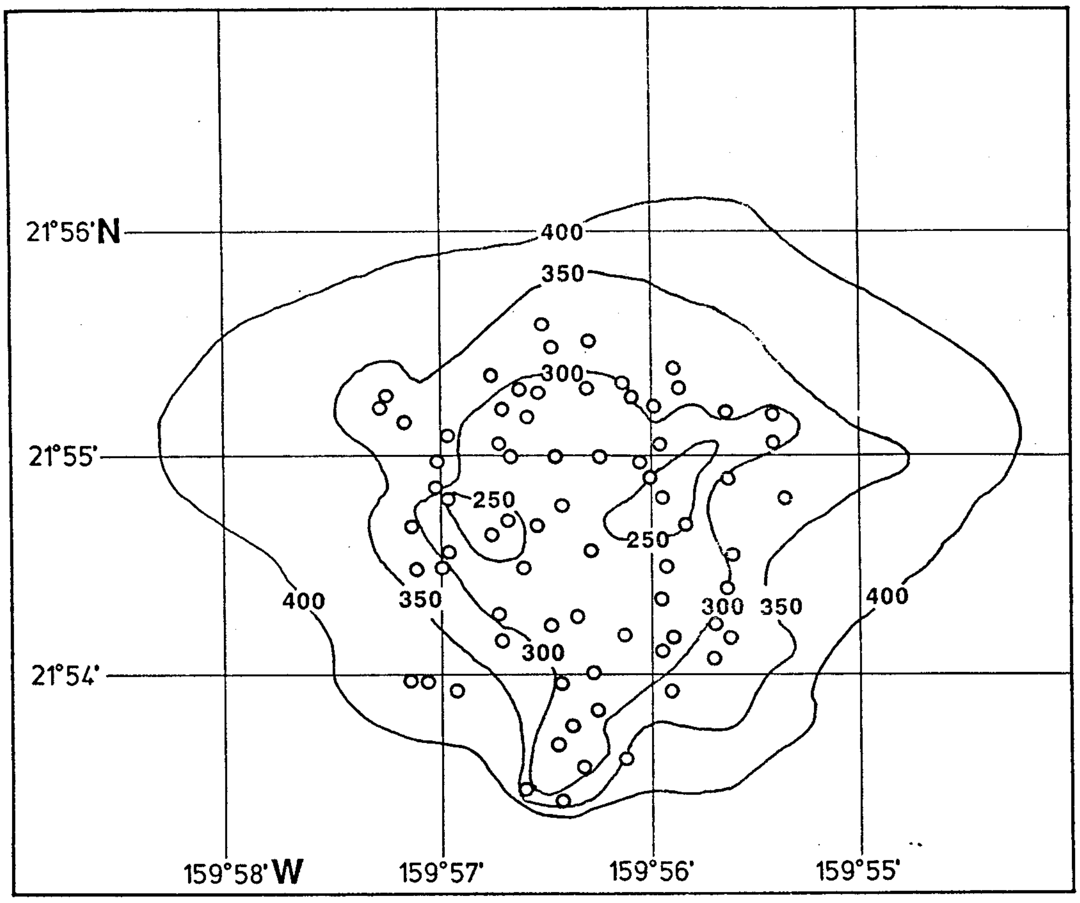

Figure 2.--Site of the intensive fishing experiment for <u>Heterocarpus</u> <u>laevigatus</u> in the Kaulakahi Channel between Kauai and Niihau. Depths in fathoms. Circles represent trap set locations.

has relatively high densities of the target species, and was fished commercially for only about 1 yr in 1984.

The intensive fishing experiment was conducted from 13 to 24 May 1986. During each of the 12 d of the experiment, 6-14 pyramid shrimp traps were set between depths of 230 and 380 fathoms. Following the Leslie method (Ricker 1975), catchability was estimated directly from the slope of the linear regression of CPUE on corrected cumulative catch; that is,

$$\begin{aligned} CPUE_i &= q\,B_i \\ &= q\,(B_o - K_i) \\ &= q\,B_o - q\,K_i\ ; \end{aligned}$$

where $CPUE_i$ is the catch per unit effort on day i (kg/trap-night), q is the catchability coefficient (trap-night^{-1}) of the pyramid traps, B_i is the average biomass (kg) present on day i, B_o is the biomass (kg) of shrimp present at the start of the experiment, and K_i is the corrected cumulative removals for day i, defined as

$$K_i = 0.5\ C_{n=i} + \sum_{n=1}^{i-1} C_n\ ,$$

where C_n (n = 1, 2, ..., i) is the catch (kg) up to and including each day i of the experiment. Note that the estimate of catchability coefficient ($\hat{q}$) pertains strictly to the stock resident in the study area, which is normalized to unit area after multiplying by 3.46 nmi^2 (i.e., the area of the study site).

Depth Stratified Sampling at Kauai and Niihau

For the next phase of the assessment, Kauai and Niihau (Fig. 3) were selected for comprehensive trapping surveys to determine abundance patterns with depth and to estimate the exploitable biomass at each island. The choice of these islands was based on the following criteria: (1) Their size and proximity to each other facilitated the survey logistically; (2) H. laevigatus is abundant at both banks; (3) the intensive fishing site lay midway between the islands; (4) very good bathymetry was available, allowing estimation of habitat areas by 50-fathom intervals; and (5) relatively few boats, which could tamper with the fishing gear, frequent the area. Twenty-six days of trapping were allotted for this portion of the assessment (11 September-6 October 1987).

A depth stratified sampling approach was taken to accomplish the work. The first 11 d (4 at Niihau and 7 at Kauai) were used to gather data on the depth distribution of the shrimp. Each day, seven traps were set along a representative depth transect running from 225 to 525 fathoms, with traps set at 50-fathom intervals. From these data, the mean and variance in CPUE

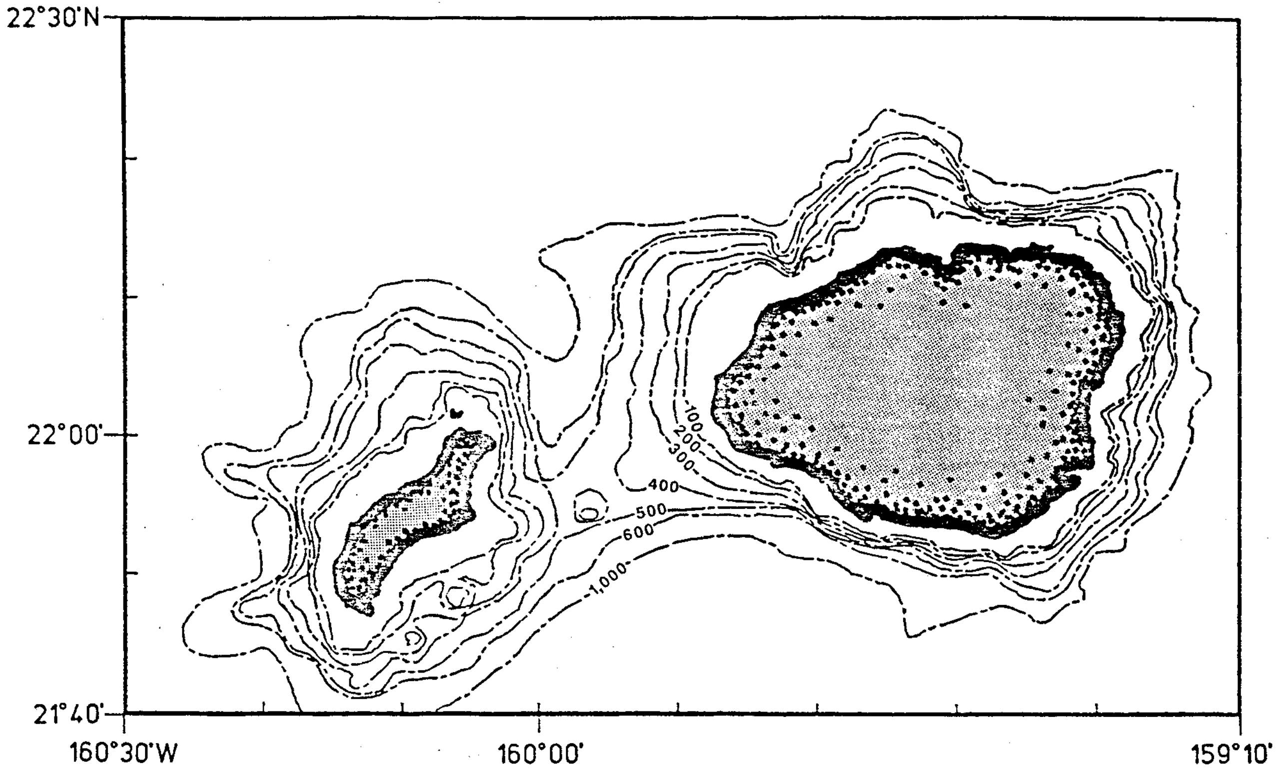

Figure 3.--Bottom contour chart of Kauai and Niihau depicting the 100-, 200-, 300-, 400-, 500-, 600-, and 1,000-fathom isobaths.

were calculated for each of the seven 50-fathom depth zones. The remaining 15 d of trapping were then used for stratified sampling. Based on the results of the vertical distribution survey, sampling effort was optimally partitioned into depth strata by Neyman allocation (Cochran 1977); that is, trap allocations at each depth were based on the product of shrimp abundance (CPUE x habitat area) and the standard deviation of CPUE at that depth.

From the results of this survey, exploitable biomass was estimated (Equation (1)) for each depth interval at the two islands. An estimate of the variance of the biomass for each stratum was obtained from Equation (1) using the delta method (Seber 1973):

$$\mathrm{VAR}\{B\} \simeq \frac{A^2}{q^2}\mathrm{VAR}\{\mathrm{CPUE}\} + \frac{\mathrm{CPUE}^2}{q^2}\mathrm{VAR}\{A\} + \frac{\mathrm{CPUE}^2\,A^2}{q^4}\mathrm{VAR}\{q\}\,, \qquad (2)$$

if all covariance terms were zero, a likely condition.

Regional Variation in Shrimp Abundance

For the last phase of the assessment, CPUE information was collected or compiled from as many of the 38 identified sites as possible. These data were then used to estimate exploitable biomass. Various data sources were combined to obtain the best possible biomass predictions for these areas, including unfished banks where no data were available. Because of constraints on vessel time, only seven additional localities were surveyed on two research cruises of the Townsend Cromwell (1-23 April 1985 and 28 February-20 March 1988). The first cruise evaluated three small isolated areas (north of French Frigate Shoals, and northwest Gardner Pinnacles No. 1 and No. 2) as potential sites for the depletion work. The second cruise made stops at Laysan Island (4 d), the vast French Frigate Shoals-Brooks Banks-St. Rogatien Bank (4 d), Oahu (1 d), and the Island of Hawaii (5 d). These latter banks were selected to provide standardized CPUE data among widely scattered localities in both the MHI and the NWHI. At each site, trap allocations by depth generally were proportional to the abundance of shrimp. Bank-specific, mean stratified catch rates ($CPUE_s$ = simple average of all traps fished at a bank) were converted to estimates of randomized catch rate ($CPUE_r$) by invoking correction factors calculated from the Kauai-Niihau study. Additional data (one overnight trap set) were collected at the Southeast Hancock Seamount in June 1985.

Catch rate data for *H. laevigatus* from other localities were available from a number of earlier research cruises. From 1975 to 1985, 13 cruises of the Townsend Cromwell included limited exploratory shrimp trapping at 15 different banks in the Hawaiian Islands (Gooding 1984). These surveys utilized smaller kamaboko-style traps, however (see Fig. 3 in Gooding 1984). The CPUE data derived from these cruises were therefore standardized to data obtained from the much larger pyramid shrimp traps. This was accomplished by regressing pyramid trap CPUE against kamaboko trap CPUE with data from the four common localities where both types of traps were fished.

For the remaining 16 locations where no data on shrimp abundance were available (11 were small sites north of Laysan Island), CPUE values were predicted with a regression of $CPUE_r$ on distance up the archipelago, as measured from Hawaii to the Hancock Seamounts. Exploitable biomass was then estimated at each site by using Equation (1).

RESULTS

Depletion Experiment

During the intensive fishing experiment, 123 pyramid shrimp traps were set at the Kaulakahi Channel study site. Of these, 19 were lost, resulting in 104 effective trap-nights of standard fishing effort and a gear loss rate of 15%. A total of 45,482 *H. laevigatus* were caught; they collectively weighed 1,499.00 kg. The average size of each shrimp was therefore 33 g (1.18 oz). During the 12-d course of the experiment, no change occurred in the mean size of shrimp caught (r = -0.043, df = 10, P = 0.67).

Daily CPUE was computed by dividing a day's catch by the number of traps fished. Catch rate calculations excluded traps that did not fish properly (e.g., the funnel entrance was ajar upon retrieval), whereas cumulative removals (K_i) included every shrimp caught in the study area (<380 fathoms). A plot of average daily CPUE against corrected cumulative removals is presented in Figure 4. Each point represents 1 d of fishing. Also presented is the linear fit of the regression equation relating these variables. The equation of the line is

$$CPUE_i = 22.69 - 0.008148\ K_i\ ,$$

with standard errors for the slope and intercept equal to 0.0021177 and 1.98664, respectively. The regression is highly significant (F = 14.81, df = 1 and 10, P = 0.0032). The correlation coefficient is r = -0.773, and the coefficient of determination is 60%. Note that in Figure 4 the residuals show no obvious departure from linearity, indicating constant catchability.

Under the Leslie model, the exploitable biomass at the start of the experiment is defined by the x-intercept, i.e., 2,785 kg. Because the study site covered 3.46 nmi², this amounts to a initial density of 804.9 kg/nmi², which produced an initial catch rate ($CPUE_o$) equal to 22.69 kg/trap-night

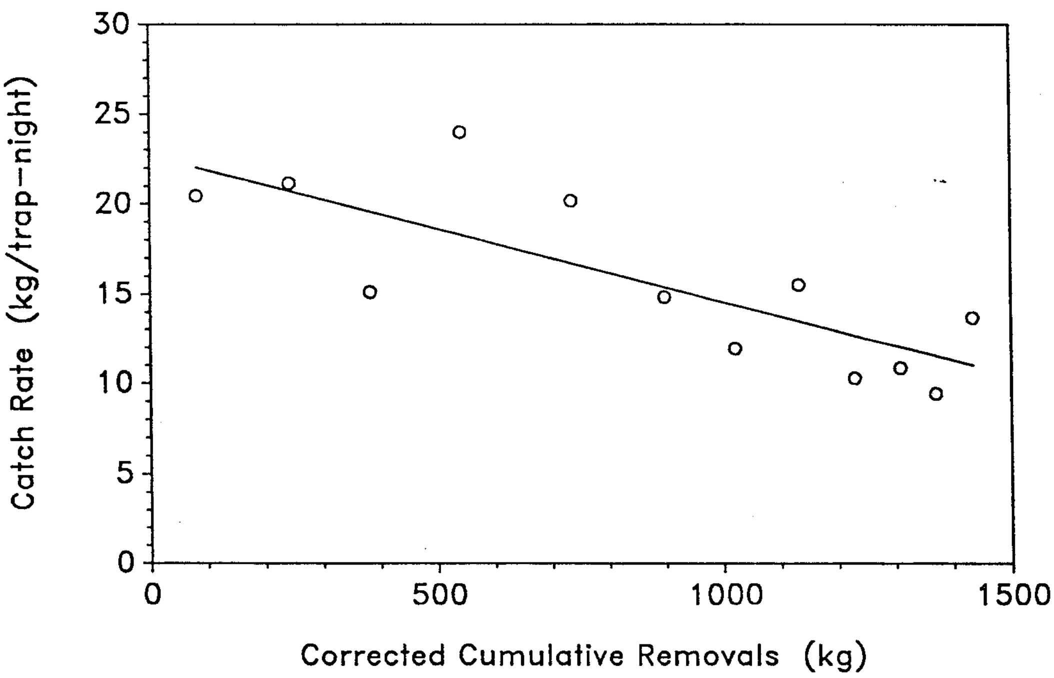

Figure 4.--Leslie model applied to the intensive fishing experiment for Heterocarpus laevigatus at the Kaulakahi Channel study site. Each point represents 1 d of fishing.

(i.e., the *y*-intercept). Thus, $\hat{q}$, expressed on the basis of a square nautical mile rather than defined in terms of the study site area, is estimated to be 0.028192 nmi^2/trap-night. In real terms, one overnight soak of a large pyramid shrimp trap captures approximately 2.8% of the shrimp in an area of 1 nmi^2.

The variance of the estimate of *q* is easily obtained. The variance of the product of a random variable (e.g., the slope of the regression) and a constant (e.g., the area of the study site) is equal to the constant squared (3.46^2) times the variance of the random variable (0.0021177^2). Thus, it follows that $VAR\{\hat{q}\} = 5.3687 \times 10^{-5}$.

It is instructive to note that an initial density of 804.9 kg/nmi^2 is equivalent to 2.3467 kg/ha or an average of 71 shrimp/ha (see calculation of mean shrimp weight above). Based on these densities, each shrimp occupied 140 m^2 of habitat, a remarkable statistic given the relatively high catch rate encountered at the beginning of the study (22.69 kg/trap-night). These figures serve to highlight the exceptional vulnerability of *H. laevigatus* to capture with baited traps.

Stratified Sampling at Kauai and Niihau

A total of 191 traps were set during the stratified sampling program at Kauai and Niihau. Initially, 76 traps were deployed to determine the depth distribution of *H. laevigatus* at Niihau ($N = 28$) and Kauai ($N = 48$). Although shrimp abundance patterns with depth were qualitatively similar at the two islands, densities at Niihau appear to be quantitatively greater than at Kauai (Fig. 5). For example, peak abundance of shrimp was in the 250- to 300-fathom stratum at both sites, but the absolute CPUE in this stratum was 61% greater at Niihau. As expected, little or no shrimp occurred at depths shallower than 250 fathoms or deeper than 500 fathoms. At both sites, the overall depth distribution of *H. laevigatus* was skewed towards greater depths, and the variance in catch rate increased with the mean (heteroscedasticity).

Based on these findings, the remaining 79 traps deployed around Kauai and the 36 traps set around Niihau were allocated to 50-fathom depth intervals according to the product of mean CPUE, the standard deviation of CPUE, and the area of each depth stratum. Estimates of these statistics were updated daily as the survey progressed. The resulting overall allocation of traps by depth zone at the two islands (Fig. 6) shows that the preponderance of traps was set in areas of maximum abundance.

At Niihau, a total of 461.07 kg of *H. laevigatus* were caught, yielding a mean CPUE of 7.20 kg/trap-night; at Kauai, total catch and mean CPUE were 447.98 kg and 3.53 kg/trap-night, respectively. Note that these statistics are largely a reflection of the specific allocation of traps to depth strata depicted in Figure 6.

The depth stratified results from Kauai and Niihau are presented in Table 1. Digitized estimates of the amount of shrimp habitat in each of

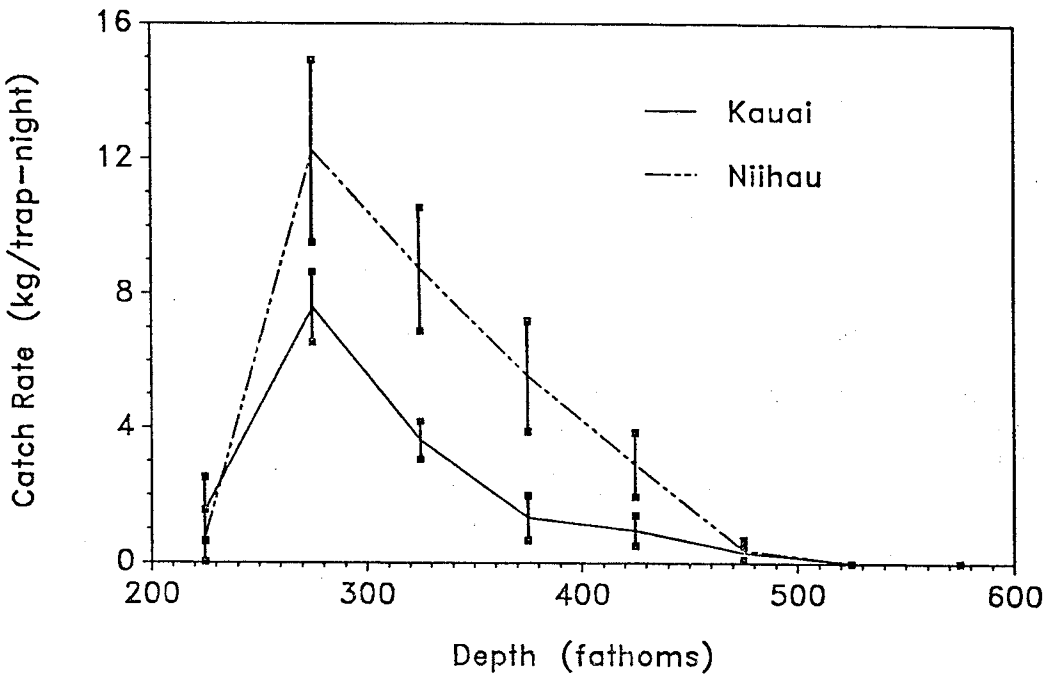

Figure 5.--Catch rate of Heterocarpus laevigatus by depth at Kauai and Niihau. Error bars are standard errors of the means.

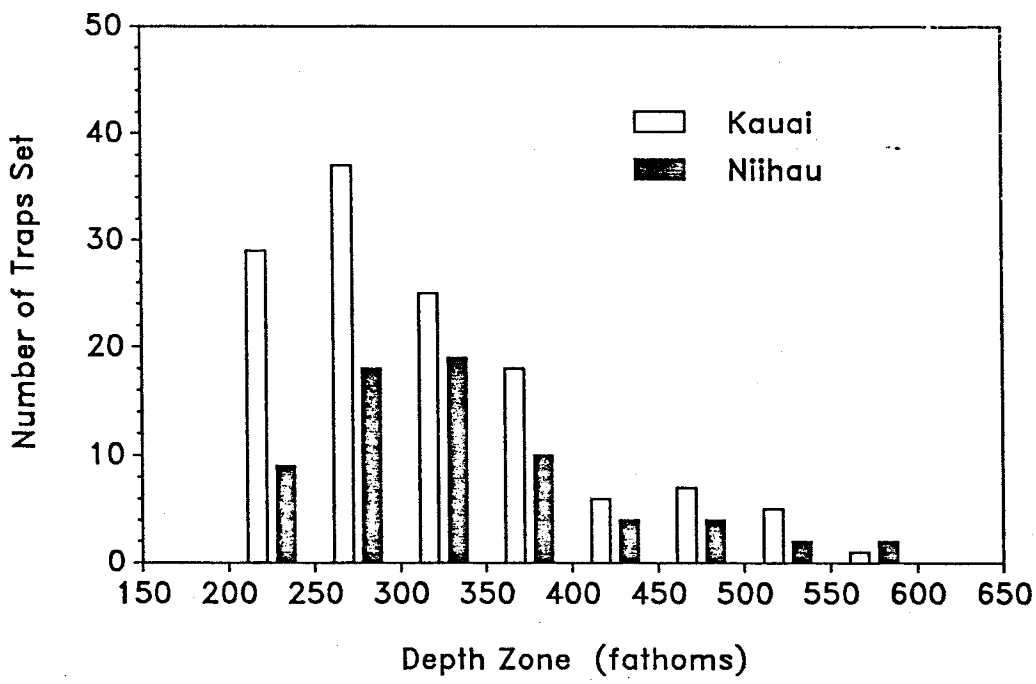

Figure 6.--Distribution of trapping effort by depth zones during the stratified sampling program at Kauai and Niihau.

Table 1.--Summary of depth stratified sampling for *Heterocarpus laevigatus* at Kauai and Niihau (CPUE = catch per unit effort; kg/trap-night).

Depth range (fathoms)	No. traps set	Mean CPUE	VAR{CPUE}	Habitat area (nmi²)	q (trap⁻¹)	Stock size (kg)[a]	VAR{STOCK}[b]
				Kauai			
200-250	29	1.566	0.894	37.2	0.028192	2066	1843569
250-300	37	7.587	1.093	35.2	0.028192	9463	7749481
300-350	25	3.607	0.322	42.0	0.028192	5370	2661974
350-400	18	1.324	0.436	49.4	0.028192	2318	1699415
400-450	6	0.953	0.203	51.8	0.028192	1752	893972
450-500	7	0.299	0.038	58.9	0.028192	625	192372
500-550	5	0.006	0	32.5	0.028192	7	3
Total	127			307.0		21601	15040787
				Niihau			
200-250	9	0.788	0.586	31.1	0.028192	869	764208
250-300	18	12.214	7.253	30.8	0.028192	13344	20690821
300-350	19	8.719	3.335	32.1	0.028192	9928	10991936
350-400	10	5.533	2.737	34.2	0.028192	6712	7079340
400-450	4	2.903	0.906	35.6	0.028192	3666	2353836
450-500	4	0.38	0.094	38.9	0.028192	524	197556
Total	64			202.7		35043	42077696

[a]For calculation, refer to Equation (1) in text.
[b]For calculation, refer to Equation (2) in text.

the 50-fathom depth intervals were fairly uniform at each island. Typically, measurement errors in determining these estimates were small (median coefficient of variation = 0.5%, range = 0.1-1.9%), and they were omitted from the table for brevity. We have no data concerning errors in the specific locations of the 250- and 500-fathom isobaths obtained from nautical charts. Because our estimates of VAR{A} do not account for this, they must be considered the minima. In Table 1, stock size was estimated by using Equation (1), and the variance in stock size was computed with Equation (2).

The depth stratified results show that, in the 200- to 550-fathom depth range, the exploitable biomass of *H. laevigatus* at Kauai ($\underline{B}_k$) was 21.6 t ($P\{14.0 \leq \underline{B}_k \leq 29.2\} = 0.95$). The total area of suitable habitat at Kauai was 307.0 nmi², resulting in a randomized average density of 70.36 kg/nmi².

Likewise for Niihau, exploitable biomass ($\underline{B}_n$) was determined to be 35.0 t ($P\{22.3 \leq \underline{B}_n \leq 47.8\} = 0.95$). There, the total estimated area of shrimp habitat was 202.7 nmi², corresponding to a randomized average density of 172.88 kg/nmi². These results show that, on average, shrimp densities were 2.46 times greater at Niihau than Kauai. Randomized $CPUE_r$ values (the product of $\hat{q}$ and randomized density) were then calculated for Kauai and Niihau, yielding 1.98 kg/trap-night and 4.87 kg/trap-night, respectively.

Regional Variation in Catch Rates

Detailed bathymetry was unavailable for most other islands and banks. Consequently, at all remaining sites, exploitable biomass was estimated over the full 250- to 500-fathom depth range, rather than by individual 50-fathom depth intervals. However, this procedure required a random sample of catch rates from the full depth range of the species ($CPUE_r$). Because trap allocations by depth were proportional to abundance in later cruises, pyramid trap CPUE statistics derived from data collected on Townsend Cromwell cruises north of French Frigate Shoals, northwest Gardner Pinnacles No. 1 and No. 2, Laysan Island, French Frigate Shoals-Brooks Banks-St. Rogatien Bank, Oahu, and Hawaii were biased estimates of randomized catch rate ($CPUE_r$), if they were simply averaged. To alleviate this problem, a correction factor was derived. First, we noted that the deployment of traps into 50-fathom depth zones was proportionately similar among the seven sites listed above ($\chi^2 = 1.98$, df = 6, $\underline{P} > 0.90$): 200-250 fathoms (2.5%), 250-300 fathoms (16.5%), 300-350 fathoms (35.4%), 350-400 fathoms (31.6%), 400-450 fathoms (11.4%), and 450-500 fathoms (2.5%).

Next, this specific allocation schedule was applied to the depth specific CPUE data collected during the Kauai-Niihau study (Table 1), to calculate the unweighted mean catch rate as if the sampling were stratified as such ($CPUE_s$). Calculations were performed for Kauai and Niihau separately, resulting in $CPUE_s$ of 3.10 and 7.21 kg/trap-night, respectively. Lastly, the ratio of $CPUE_r/CPUE_s$ was taken at the two islands, providing a correction factor ($\underline{c}$) for converting $CPUE_s$ statistics to $CPUE_r$ statistics, under the specified trap allocation schedule. The results were $\underline{c} = 0.64$ for Kauai and $\underline{c} = 0.68$ for Niihau. Based on the similarity of the estimates, we concluded that $CPUE_r = 0.66\ CPUE_s$.

Presented in Table 2 are the results of pyramid trap samples at 21 sites in the Hawaiian Archipelago. An estimate of mean $CPUE_r$ from random samples in the 250- to 500-fathom depth range at each island or bank was obtained by taking the unweighted average catch rate from all traps fished ($CPUE_s$) and multiplying by the correction factor derived from the Kauai-Niihau study (0.66). Also presented are the data from Gooding (1984), based on research sampling with kamaboko shrimp traps, and commercial catch rate data obtained from the fishing vessel Mokihana (Tagami and Barrows 1988).

The relationship between randomized pyramid trap catch rates and those from Gooding (1984) was investigated with weighted regression analysis (Fig. 7). Statistical weights for each of the four localities

Table 2.--Summary of *Heterocarpus laevigatus* CPUE (kg/trap-night) statistics for various Hawaiian localities. *Townsend Cromwell* data were gathered during research sampling with large pyramid traps. Gooding (1984) data were obtained during research sampling with small kamaboko traps. *Mokihana* data were commercial data based on the larger pyramid shrimp traps. $CPUE_s$ = mean catch rate of traps allocated to depths in proportion to shrimp abundance (see text). $CPUE_r$ = estimated catch rate of shrimp if traps were randomly placed in the 250- to 500-fathom depth range.

Location	*Townsend Cromwell*			Gooding (1984)		*Mokihana*	
	$CPUE_s$	$CPUE_r$	*N*	CPUE	*N*	CPUE	*N*
Hawaii	4.72	3.12	31	1.58	44	10.4	1454
Oahu	4.29	2.83	8	--	--	12.9	370
Kauai	3.10	1.98	127	--	--	--	--
Niihau	7.21	4.87	64	--	--	17.1	1803
Nihoa	--	--	--	0.99	17	6.2	86
Twin Banks	--	--	--	0.74	6	9.7	724
Necker Island	--	--	--	1.06	62	8.4	297
French Frigate Shoals-Brooks Banks-St. Rogatien Bank	1.32	0.87	30	0.52	71	9.8	1765
North of French Frigate Shoals	0.89	0.59	4	--	--	--	--
Gardner Pinnacles	--	--	--	1.56	48	8.1	375
Northwest Gardner Pinnacles No. 1	1.45	0.96	9	--	--	--	--
Northwest Gardner Pinnacles No. 2	4.65	3.07	5	--	--	--	--
Raita Bank	--	--	--	1.27	8	--	--
Maro Reef	--	--	--	0.92	27	--	--
Laysan Island	0.59	0.39	18	0.05	4	--	--
Northampton Seamount	--	--	--	0.06	16	--	--
Lisianski Island	--	--	--	0.02	9	--	--
Salmon Bank	--	--	--	0.06	8	--	--
Ladd Seamount	--	--	--	0.10	4	--	--
Bank No. 11	--	--	--	0.00	4	--	--
Southeast Hancock Seamount	--	0.00	1	0.00	4	--	--

where data occurred in common (Hawaii, the French Frigate Shoals region, Laysan Island, and Southeast Hancock Seamount) were calculated as the geometric mean of the two sample sizes. Ordinary regression of $CPUE_r$ on the Gooding (1984) data resulted in an intercept term not significantly different from zero (t = -0.398, P = 0.73). The data were therefore refitted to a zero-intercept model, resulting in

$$CPUE_r = 1.94\ CPUE_g ,$$

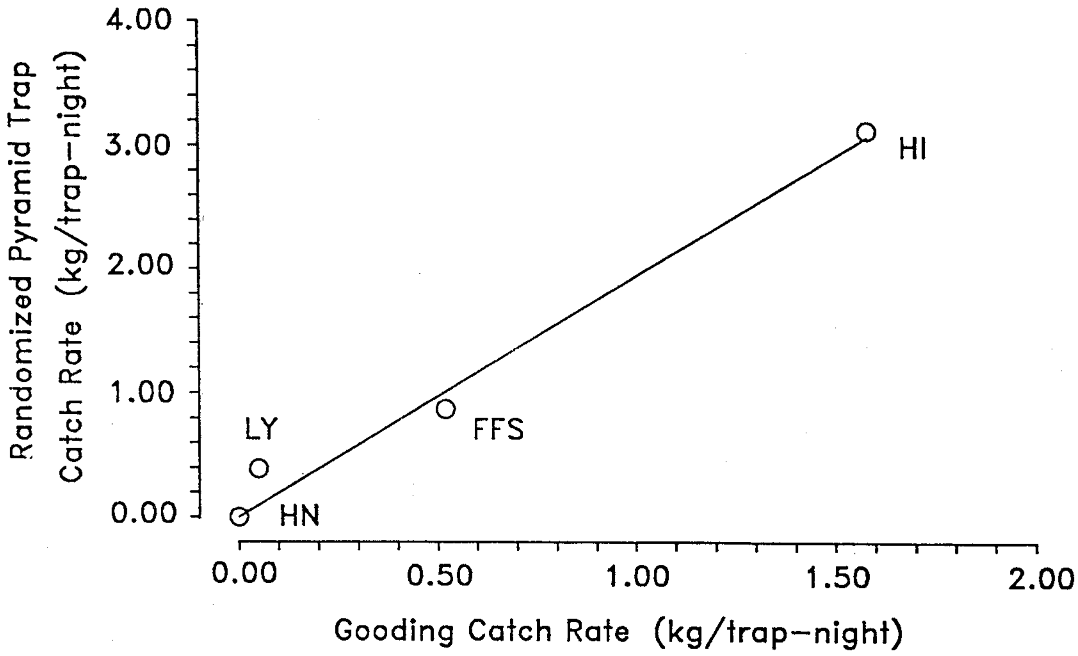

Figure 7.--The relationship between randomized pyramid trap catch per unit effort (CPUE) and Gooding (1984) CPUE (HN = Southeast Hancock Seamount, LY = Laysan Island, FFS = French Frigate Shoals, HI = Hawaii). Data from Table 2.

where $CPUE_g$ represents catch rate data from Gooding (1984). The coefficient of determination for this regression was $r^2 = 0.996$, indicating precise predictive capability for the equation. Moreover, data from the entire range of the archipelago were used in developing the regression, although sample size was small ($N = 4$ banks).

The regression equation was used to estimate randomized pyramid trap catch rates at localities sampled by Gooding (1984), but where no pyramid trap data existed. There were 11 such areas, including Nihoa, Twin Banks, Necker Island, Gardner Pinnacles, Raita Bank, Maro Reef, Northampton Seamount, Lisianski Island, Salmon Bank, Ladd Seamount, and Bank No. 11. The resulting predictions are presented in Table 3, along with actual $CPUE_r$ data acquired directly from the *Townsend Cromwell* in those situations where cruise data were available.

Even with predictions of $CPUE_r$ based upon the Gooding (1984) data, catch rate information was still lacking for 16 of the 38 identified localities in the archipelago. Therefore, a regression of $CPUE_r$ on linear distance up the Hawaiian Islands (Fig. 8) was used to estimate $CPUE_r$ for sites where no data were available. The regression was highly significant ($F = 22.06$, df = 1 and 19, $P = 0.0002$), with a coefficient of determination equal to 54%. The specific linear regression equation was

$$CPUE_r = 3.473 - 0.002381 \text{ (Dist)} ,$$

Table 3.--Identified potential locations for shrimp in the Hawaiian Islands with positions (latitude and longitude), distances up the chain, habitat areas, randomized estimates of catch rate, and projected stock sizes (t = metric tons). See text for further discussion.

Location	Lat. N	Long. W	Dist. (nmi)	Area (nmi^2)	$CPUE_r$ (kg/trap)	Stock (t)
Hawaii	19.5	155.5	39	676	3.12	74.8
Maui-Lanai-Molokai	21.0	156.6	144	1212	3.13	134.6
Oahu	21.5	158.0	221	726	2.83	72.9
Kauai	22.1	159.5	317	307	1.98	21.6
Kaulakahi Channel	21.9	159.9	330	3	22.69	2.8
Niihau	21.8	160.1	337	203	4.87	35.0
Kaula Island	21.6	160.5	356	18	2.63	1.7
Total main Hawaiian Islands				3145	3.08	343
Middle Bank	22.7	161.0	404	31	2.51	2.8
Nihoa	23.0	161.9	462	99	1.92	6.8
Twin Bank No. 1	23.3	162.7	510	83	2.26	6.7
Twin Bank No. 2	23.2	163.1	519	79	1.44	4.1
Twin Bank No. 3	23.3	163.6	526	26	2.22	2.1
Necker Island	23.6	164.7	606	251	2.06	18.3
North of French Frigate Shoals	24.3	166.1	702	22	0.59	0.5
French Frigate Shoals-Brooks Banks-St. Rogatien Bank	24.0	166.7	721	888	0.87	27.4
Gardner Pinnacles	25.0	168.0	817	444	3.03	47.7
NW Gardner Pinnacles No. 1	25.3	168.5	846	20	0.96	0.7
NW Gardner Pinnacles No. 2	25.4	168.6	865	25	3.05	2.7
Raita Bank	25.6	169.6	904	81	2.46	7.1
Maro Reef	25.5	170.6	962	239	1.78	15.1
Laysan Island	25.7	171.7	1029	46	0.39	0.6
Northampton Seamount No. 1	25.3	172.1	1038	25	1.00	0.9
Northampton Seamount No. 2	25.5	172.4	1048	117	0.12	0.5
Pioneer Bank	26.0	173.4	1125	92	0.79	2.6
Lisianski Island	26.0	174.0	1154	84	0.04	0.1
Bank No. 8	26.3	174.6	1212	14	0.59	0.3
Bank No. 9	27.0	175.6	1250	7	0.50	0.1
Salmon Bank	26.9	176.5	1298	48	0.12	0.2
Pearl and Hermes Reef	27.8	175.8	1298	69	0.38	0.9
Ladd Seamount	28.5	176.7	1356	16	0.19	0.1
Midway	28.2	177.4	1385	36	0.18	0.2
Nero Bank	28.0	178.0	1413	6	0.11	0.0
Kure Atoll	28.4	178.4	1442	65	0.04	0.1
Bank No. 10	29.0	178.7	1471	12	0.00	0.0
Bank No. 11	28.9	179.6	1490	15	0.00	0.0
Bank No. 12	30.4	178.2	1452	15	0.02	0.0
Southeast Hancock Seamount	29.8	180.9	1577	5	0.00	0.0
Northwest Hancock Seamount	30.3	181.3	1587	5	0.00	0.0
Total Northwestern Hawaiian Islands				2966	1.41	148
Grand total				6111		492

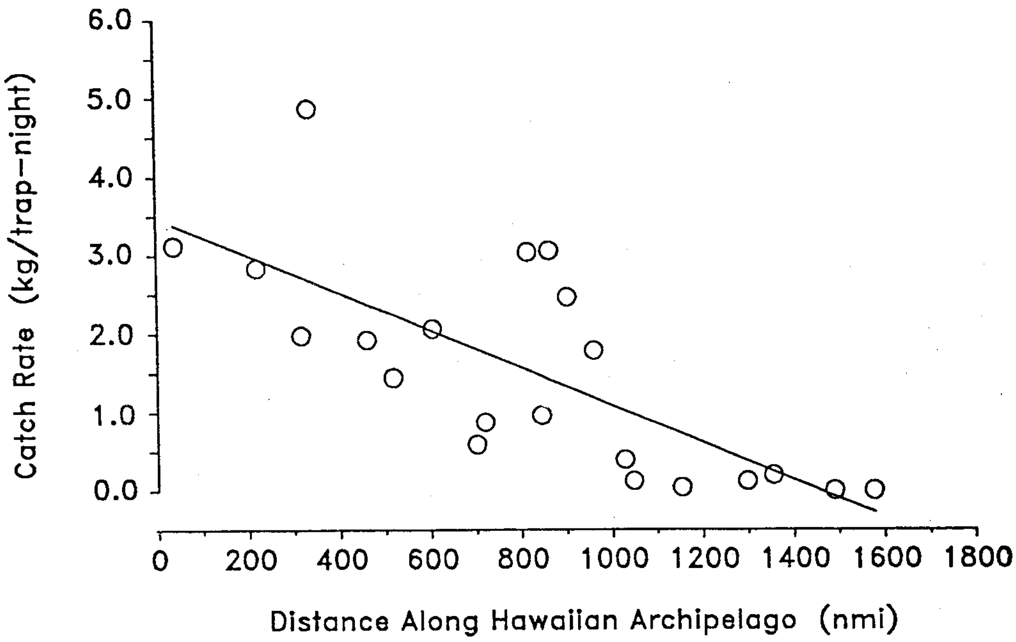

Figure 8.--The relationship between standardized $CPUE_r$ of Heterocarpus laevigatus and distance up the Hawaiian Archipelago. Data from Table 3.

where (Dist) was the distance (nmi) up the chain, measured from a point situated at lat. 19.0°N, long. 155.0°W to the center of each island or bank.

With data on $CPUE_r$ (randomized pyramid trap catch rate) at each of the 38 identified localities, an estimate of q, and measurements of the amount of suitable shrimp habitat at each site, we estimated the exploitable biomass of H. laevigatus at each location by using Equation (1) (Table 3). Results show that standing stocks are equal to 343 t of shrimp in the MHI and 148 t in the NWHI, spread over 3,145 and 2,966 nmi^2, respectively. Using these figures to calculate the mean density of shrimp in each region, and multiplying by $\hat{q}$, produced an estimate of the average $CPUE_r$ for the MHI equal to 3.08 kg/trap-night. The corresponding figure for the NWHI was 1.41 kg/trap-night. These data suggest that the density of shrimp in the MHI is 2.2 times greater, on average, than in the NWHI. The estimated exploitable biomass of H. laevigatus is 492 t in the entire Hawaiian Archipelago. Given the 6,111 nmi^2 of shrimp habitat to support this stock, the archipelago-wide average catch rate of shrimp for traps set at random in the 250- to 500-fathom depth range is 2.27 kg/trap-night.

The sex-specific size structure of the pyramid trap catches, pooled from all areas sampled by the Townsend Cromwell, is shown in Figure 9. Note that many more males were caught than females and that females grow to a larger size.

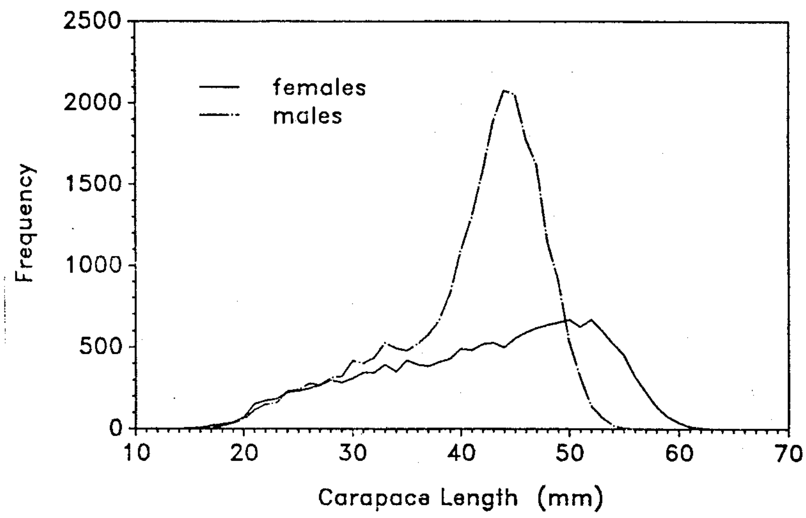

Figure 9.--Size-frequency distribution of male and female Heterocarpus laevigatus.

DISCUSSION

To a large extent, the validity of this assessment rests upon the quantitative prediction of regional variation in CPUE statistics. To assist in meeting this goal, data from Gooding (1984) were standardized to randomized pyramid trap catch rates (see Fig. 7). Likewise, a clinal decline in shrimp abundance to the northwest was revealed (Fig. 8), analogous in many respects to Turner's (1977) finding that the yield of penaeid shrimp stocks declines with increasing latitude.

Catch rate data from another source (Tagami and Barrows 1988) are available for comparison with our findings (see Table 2). This earlier work describes the fishing activity of the Mokihana during 1983-84. Catch rate statistics from a commercial vessel are unlikely to be strictly proportional (i.e., linear with zero-intercept) to overall shrimp density. Still, there is a significant positive correlation between catch rates of the Mokihana and our estimates of randomized pyramid trap catch rate (Fig. 10), based on data from the eight localities where CPUE statistics are held in common. This finding supports the specific patterns in shrimp abundance that we have described and lends credence to our estimates of exploitable biomass.

In their study of the growth and mortality of H. laevigatus in Hawaii, Dailey and Ralston (1986) estimated the total mortality rate as $Z = 0.73\ yr^{-1}$ for female shrimp and $Z = 1.51\ yr^{-1}$ for male shrimp. Because the size-frequency data used in their analysis were obtained from an unfished stock, it can be assumed that these represent reasonable estimates of sex-specific natural mortality rate. Moreover, Gulland (1971) suggested that

$$\hat{MSY} = 0.5\ M\ B_o\ , \qquad (3)$$

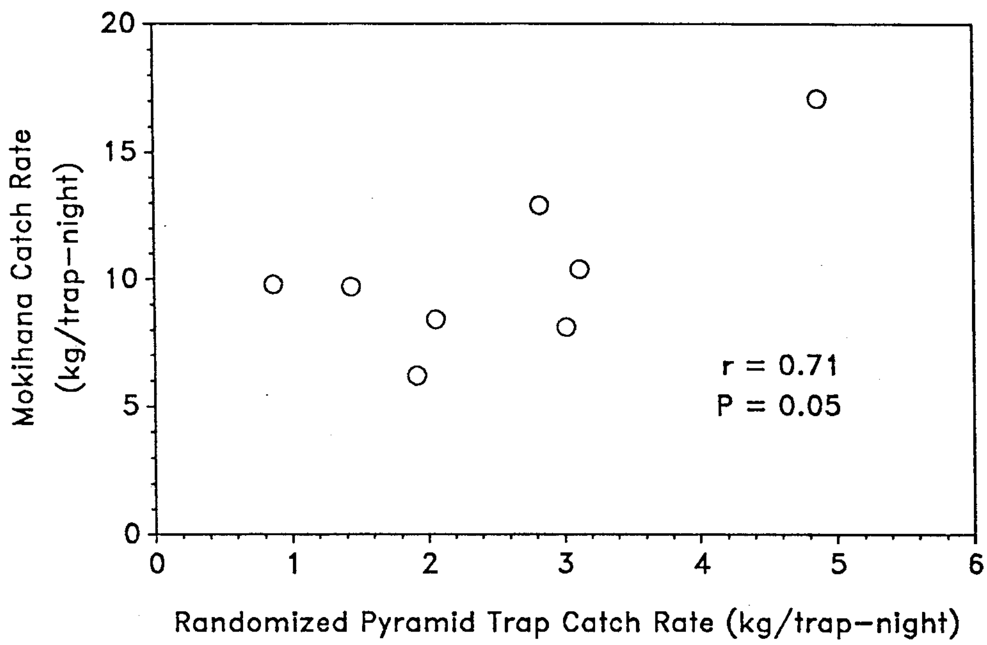

Figure 10.--The relationship between Mokihana catch rates and $CPUE_r$. Data from Table 2.

where B_o is the virgin exploitable biomass. If half of the Hawaiian stock, which is basically unexploited, is female and half is male, this leads to

$$\hat{MSY} = 0.5\ (0.73)\ (246) + 0.5\ (1.51)\ (246) = 276\ t/yr.$$

Although Equation (3) has been used extensively in the past, it is overly simplistic and lacks theoretical rigor. We, therefore, place little confidence in this particular estimate of MSY.

In a somewhat more sophisticated approach to estimating Heterocarpus yields, Moffitt and Polovina (1987), through methods similar to those used here, determined that the virgin exploitable biomass of H. laevigatus in the Mariana Archipelago (including Guam) was 677 t. Additionally, MSY was estimated in two different ways: (1) according to Gulland's (1983, 1984) $F_{0.1}$ criterion and (2) according to a consideration of minimum spawning stock biomass (i.e., reduction of spawning stock biomass to no less than 20% of virgin levels). In the former analysis, MSY was calculated to be 192 t/yr, and in the latter, MSY was 162 t/yr. These figures indicate that, for stocks of H. laevigatus in the Marianas, the ratio of MSY to virgin exploitable biomass is 0.24-0.28. If similar stock dynamics prevail in the Hawaiian Islands, where the size structure of shrimp catches (Fig. 8) is quite similar to those observed in the Marianas (e.g., Fig. 4 in Ralston 1986), then a projected MSY for the Hawaiian Islands should be in the range of 118 to 138 t/yr.

Other researchers have speculated on the magnitude of the Hawaiian Heterocarpus resource ever since early surveys indicated that catch rates were high enough to support a commercial fishery. Struhsaker and Aasted (1974) concluded that Heterocarpus spp. represent "an unexploited world resource of considerable magnitude" and that shrimp biomass probably "exceeds that of any commercially exploitable tropical crustacean." Based on the highly productive trawl fishery for H. reedi off the coast of Chile ($12.5\ t \cdot km^{-2} \cdot yr^{-1}$), they held that an annual yield of 1-2 t/km^2 was a reasonable estimate for MHI waters. Based on the same production figures from the Chilean fishery, the Hawaii Division of Aquatic Resources (HDAR) estimated shrimp productivity to be $0.7\ t \cdot km^{-2} \cdot yr^{-1}$, and suggested an annual yield of 450-900 t could be realized from a potential fishing area of 10,290 km^2 ([Hawaii] DLNR 1979). Oishi (1983), based on an economic feasibility study, concluded that Hawaii's local market could absorb about 15-65 t/yr and that an export market, primarily to Japan, could account for an additional 200-300 t/yr harvest of Heterocarpus spp. Likewise, a commercial operator projected a 500 t/yr harvest in 1984, which would require 2,500-5,000 t of exploitable biomass to support (Methot[2]). The Council (1984), using many of the same assumptions, reported potential annual yields ranging from 400 to 4,000 t. Lastly, Polovina[3] estimated an MSY of 830 t/yr.

Although these projections of potential yield vary among themselves, they all are substantially higher than the MSY estimated in this study, i.e., about 125 t/yr. Somewhat surprisingly, our estimate of the exploitable biomass for the entire Hawaiian Archipelago was determined to be approximately 500 t, with 70% of the biomass resident in the MHI. Our results indicate that the H. laevigatus resource is not nearly as large as has been previously conjectured. When fully exploited, at today's prices, the fishery could produce roughly $1 million ex-vessel. This represents only about 15-20% of the value of either the Hawaiian bottom fish or lobster fishery.

There are several possible explanations for the great disparity in estimates of MSY. Struhsaker and Aasted (1974) and HDAR ([Hawaii] DLNR 1979) based their projections on the Chilean shrimp fishery. Comparisons and extrapolations of productivity from this fishery to Hawaii's situation are unrealistic for a number of reasons. First, the target species are different (H. reedi is unknown in Hawaiian waters). Second, the Chilean fishery is located in the highly productive upwelled waters of the Humboldt Current. Third, theirs is a shallow water trawl fishery rather than a deepwater trap fishery. Moreover, Methot (footnote 2) and the Council (1984) based their estimates on shrimp trapping results from the Mariana Archipelago. Although

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[2]Methot, R. 1984. Analysis of the potential yield of Hawaiian deepwater shrimp, 5 p. Unpubl. manuscr. Southwest Fisheries Center, National Marine Fisheries Service, NOAA, P. O. Box 271, La Jolla, CA 92038.

[3]Polovina, J. J. 1985. Marianas deepwater shrimp data analyzed. Southwest Fisheries Center, Report of Activities, January-February 1985, p. 3-4.

the traps used there were very similar to those described in Gooding (1984), the relationship between catch rate and shrimp density in the Marianas, where the seafloor is often basaltic, need not be the same as in Hawaii, where it is typically limestone.

Another major cause of discrepancy lies in calculating the potential fishing area or area of suitable habitat. The Council (1984) projected an area equal to 3,874 nmi^2 (13,290 km^2) between the 100- and 400-fathom isobaths in the MHI; Struhsaker and Aasted (1974) estimated 3,587 nmi^2 (12,305 km^2) for the same area. Our estimate of 3,145 nmi^2 (10,787 km^2) covers the area between the 250- and 500-fathom isobaths, a more realistic range for H. laevigatus. This situation is further complicated by a possible lack of habitat homogeneity within these areas. It is unlikely, for example, that all areas are equally fishable and have similar types of shrimp habitat.

In spite of the somewhat low estimates of exploitable biomass and MSY, they are based upon the best information available. The CPUE statistics we used comprise the largest and most complete data base of shrimp abundance in Hawaii. Moreover, all interpolations and predictions made for the geographical survey of abundance are based on results derived from and pertaining to the area of study. Still better estimates of abundance could be acquired, but this would require additional systematic surveys of those banks where no data are presently available.

LITERATURE CITED

Clarke, T. A.
1972a. Exploration for deep benthic fish and crustacean resources in Hawaii. Univ. Hawaii, Hawaii Inst. Mar. Biol., Honolulu, Tech. Rep. 29, 18 p.

1972b. Collections and submarine observations of deep benthic fishes and decapod Crustacea in Hawaii. Pac. Sci. 26:310-317.

Cochran, W. G.
1977. Sampling techniques. John Wiley & Sons, N.Y., 428 p.

Dailey, M. D., and S. Ralston.
1986. Aspects of the reproductive biology, spatial distribution, growth, and mortality of the deepwater caridean shrimp, Heterocarpus laevigatus, in Hawaii. Fish. Bull., U.S. 84:915-925.

Gooding, R. M.
1984. Trapping surveys for the deepwater caridean shrimps, Heterocarpus laevigatus and H. ensifer in the Northwestern Hawaiian Islands. Mar. Fish. Rev. 46(2):18-26.

Gulland, J. A.
1971. The fish resources of the ocean. Fish. News (Books) Ltd., Surrey, England, 255 p.

1983. Fish stock assessment. A manual of basic methods. John Wiley & Sons, N.Y., 223 p.

1984. Advice on target fishery rates. Fishbyte [ICLARM] 2(1):8-11.

[Hawaii] Department of Land and Natural Resources (DLNR).
1979. Hawaii fisheries development plan. Department of Land and Natural Resources, State of Hawaii, 297 p.

1986. Hawaii fisheries development plan, 1985. Division of Aquatic Resources, Department of Land and Natural Resources, State of Hawaii, 163 p.

Moffitt, R. B., and J. J. Polovina.
1987. Distribution and yield of the deepwater shrimp Heterocarpus resource in the Marianas. Fish. Bull., U.S. 85:339-349.

Oishi, F.
1983. Shrimp industry development project. Division of Aquatic Resources, Department of Land and Natural Resources, State of Hawaii (State of Hawaii and Pacific Fish Development Foundation Project), 36(a), 22 p.

Ralston, S.
1986. An intensive fishing experiment for the caridean shrimp, Heterocarpus laevigatus, at Alamagan Island in the Mariana Archipelago. Fish. Bull., U.S. 84:927-934.

Ricker, W. E.
1975. Computation and interpretation of biological statistics of fish populations. Fish. Res. Board Can. Bull. 191, 382 p.

Seber, G. A. F.
1973. The estimation of animal abundance. Hafner Press, N.Y., 506 p.

Struhsaker, P., and D. C. Aasted.
1974. Deepwater shrimp trapping in the Hawaiian Islands. Mar. Fish. Rev. 36(10):24-30.

Tagami, D. T., and S. Barrows.
1988. Deep-sea shrimp trapping Heterocarpus laevigatus in the Hawaiian Archipelago by a commercial fishing vessel. U.S. Dep. Commer., NOAA Tech. Memo. NMFS, NOAA-TM-NMFS-SWFC-103, 14 p.

Turner, R. E.
1977. Intertidal vegetation and commercial yields of penaeid shrimp. Trans. Am. Fish. Soc. 106:411-416.

Western Pacific Regional Fishery Management Council (Council).
1984. Status of fisheries assessment of development and management needs for selected crustacean species in the western Pacific region. Western Pacific Regional Fishery Management Council, Honolulu, Hawaii, 60 p.